**Title:** Key somatic variables associated with, and differences between the 4 swimming strokes.

**Running title:** Somatic differences between the 4 swimming strokes

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**Abstract**

This study identified key somatic and demographic characteristics that benefit all swimmers and, at the same time, identified further characteristics that benefit only specific swimming strokes. Three hundred sixty-three competitive-level swimmers (male [n=202]; female [n=161]) participated in the study. We adopted a multiplicative, allometric regression model to identify the key characteristics associated with 100 m swimming speeds (controlling for age). The model was refined using backward elimination. Characteristics that benefited some but not all strokes were identified by introducing stroke-by-predictor variable interactions. The regression analysis revealed 7 "common" characteristics that benefited all swimmers suggesting that all swimmers benefit from having less body fat, broad shoulders and hips, a greater arm span (but shorter lower arms) and greater forearm girths with smaller relaxed arm girths. The 4 stroke-specific characteristics reveal that backstroke swimmers benefit from longer backs, a finding that can be likened to boats with longer hulls also travel faster through the water. Other stroke-by-predictor variable interactions (taken together) identified that butterfly swimmers are characterized by greater muscularity in the lower legs. These results highlight the importance of considering somatic and demographic characteristics of young swimmers for talent identification purposes (i.e., to ensure that swimmers realize their most appropriate strokes).

**Keywords:** Swim speed; talent identification; limb dimensions; ratios; allometric models; log-linear regression

## Introduction

Many clubs and national federations invest substantial resources into the identification of young gifted or talented athletes to ensure that the most promising receive high-quality coaching and training conditions (Williams, & Reilly, 2000). Anthropometric characteristics are known to be an important factor in identifying talented athletes at an early age (Morais, Jesus, Lopes, Garrido, Silva, Marinho, & Barbosa, 2012; Morais, Silva, Marinho, Lopes, & Barbosa, 2017). The fact that anthropometric characteristics are influenced less by training compared with other physical-fitness attributes highlights the importance of investigating and/or studying anthropometrics when trying to identify early athletic potential.

Recently, a number of studies have reported strong associations between human physical characteristics and sports performance (Geladas, Nassis, & Pavlicevic, 2005; Negra, Chaabene, Hammami, Khlifa, Gabett, & Hachana, 2016; Nevill, Oxford, & Duncan, 2015; Sammoud, Nevill, Negra, Bouguezzi, Chaabene, & Hachana, 2017; Sammoud, Nevill, Negra, Bouguezzi, Chaabene, & Hachana, 2018; Sammoud, Nevill, Negra, Bouguezzi, Chaabene, & Hachana, 2019). These studies highlighted the importance of determining the association between anthropometric characteristics and sports performance in order to engage children in appropriate long-term athletic development programmes.

In swimming, talent identification and development processes play a crucial role in the pursuit of excellence across a long-term career. In this regard, anthropometric characteristics are arguably one of the most important factors in swimmers achieving a high-performance level in their careers (Geladas et al. 2005; Lätt et al. 2010). While, these studies identified important characteristics associated with swimming performance, they did this for each stroke separately (Nevill et al. 2015; Sammoud et al.2017; Sammoud et al. 2018; Sammoud et al. 2019a; Sammoud et al.2019b; Jurimae, Cicchella, Latt, Purge, Leppik, & Jurimae, 2007). For example, Sammoud et al. (2017) revealed that 100-m butterfly speed performance was strongly and positively associated with the segment length ratio [(arm-span)/(forearm-length) and girth ratio (calf-girth)/(ankle-girth), rather than the whole-body size characteristics. More recently, Sammoud et al. (2018) reported positive associations between 100-m breaststroke performance and limb-girth ratio (girth ratio = forearm girth/wrist girth) in young swimmers whose mean age was 12 ± 1.2 years.

Nevill et al. (2015) revealed that lean body mass was the singularly most important whole-body characteristic associated with front crawl swim speeds and that having greater limb segment length ratios [i.e., arm ratio = (lower arm)/ (upper arm); foot-to-leg ratio = (foot)/ (lower-leg)] were key to personal best swim speeds. Lätt et al. (2010) indicated that anthropometrical factors explained 45.8% of 100-m front crawl swimming performance in male swimmers aged 15 years. Santos et al. (2012) found a positive association ($r = 0.68$) between the arm muscle area and the propulsive force of the arm in young swimmers (9-14 years old), with the increased arm muscle area contributing to a greater capacity for strength. Another study by Moura et al (2014) showed a positive association between the propulsive force of the arm and body height ($r = 0.34$; $p = 0.013$), arm span ($r = 0.29$; $p = 0.042$), sitting height ($r = 0.36$; $p = 0.009$), % body fat ($r = 0.33$; $p = 0.016$), lean body mass ($r = 0.34$; $p = 0.015$) and arm muscle area ($r = 0.31$; $p = 0.026$). Likewise, Fritzdorf et al. (2009) reported that taller and bigger swimmers with longer stroke lengths can produce more force per-stroke. In contrast, smaller swimmers whose stroke lengths are shorter will invariably utilize a higher stroke rate when competing.

Bond et al. (2015) suggested that anthropometric variables accounted for 63.8% of 100-m freestyle swimming’s total variance in a 13-year-old male and female swimmers. Similarly, Geladas et al. (2005) examined the association between anthropometric measures and swimming performance in male and female swimmers aged 12-to-14 years. They showed that upper extremity length was associated with a 100-m freestyle performance in males while upper extremity length, height, and hand-length were significantly related to performance in females. Recently, the main anthropometric determinants of backstroke swimming performance have been examined in young swimmers aged 13-14 years (Sammoud et al. 2019a). The authors revealed that forearm girth, as well as arm relaxed girth, is among the main backstroke performance indicators. More recently, Sammoud et al. (2019b) indicated that length ratio= ([height/leg length]), foot length and ankle girth, biacromial breadth (shoulder width) and % of body fat were associated with 100-m front crawl mean swimming speed performance.

As far as we are aware, however, no study has attempted to identify the key somatic and demographic characteristics that are common for all strokes, but at the same time, to identify other characteristics that benefit only specific/individual strokes. Therefore, the purpose of this article was to explore which key somatic and demographic characteristics are common to all swimmers and, in addition, to identify further characteristics that benefit only specific strokes, i.e. that are "stroke specific".

## Methods

### Participants

In total three hundred sixty-three competitive-level swimmers (male [n=202]; female [n=161]) participated to this investigation (Front-crawl swimmers: n=74, Butterfly swimmers: n=167, Backstroke swimmers: n=63, and Breaststroke swimmers: n=59) (demographic details described in Table 1). The majority of swimmers (n=145) contributed to just one swimming-stroke cohort. Eighty-three swimmers (n=83) contributed to two swimming-stroke cohorts (on separate occasions), sixteen swimmers (n=16) contributed to 3 and just one swimmer (n=1) contributed to all 4 swimming-stroke cohorts. We acknowledge that some of these data/details have been published previously, but crucially in isolation (Butterfly [Sammoud et al., 2018a]; Breaststroke [Sammoud et al., 2018b]; Backstroke [Sammoud et al., 2019]).

All participants were involved in five to six training sessions per week (4000 ± 1000 m per session; 8 ± 1 hour per-week). In addition, the training session included the four-stroke. Written informed parental consent and participant assent were obtained prior to the start of the study. All youth athletes and their parents / legal representatives were informed about the experimental protocol and its potential risks and benefits before the commencement of the research project. The study was approved by the local Ethics Institutional Review Committee for the ethical use of human subjects at Ksar Saïd University, Tunisia.

**Anthropometric and somatic measurements**

All the anthropometric measurements were taken by one trained anthropometrist assisted by a recorder in accordance with standardized procedures of the international society for the advancement of kinanthropometry (ISAK) (Stewart, Marfell-Jones, Olds, & de Ridder, 2011) (Table 1).

Testing was carried out in a standardized order after proper calibration of the measuring instruments. Each swimmer's height (m) and body-mass (kg) were assessed to the nearest 0.1 cm and 0.1 kg, using a SECA stadiometer and a SECA weighing scale (SECA Instruments Ltd, Hamburg, Germany), respectively. Skinfolds measurements (in millimeters) were taken on the right-hand side of the body at two sites (the triceps and the subscapular) using Harpenden skinfold calipers (Harpenden Instruments, Cambridge, UK). Skinfold data, alongside the skinfold equation of Slaughter et al. (1988), were used to estimate the body-fat mass and fat-free mass. The following limb-lengths, girths and breadths were assessed using a large sliding caliper and a non-stretchable tape measure via direct measures using landmarks techniques: arm span, upper-limb length, upper-arm length, lower-arm length, hand lengths, lower-limb length, thigh length, leg length, foot length, arm-relaxed girth, forearm girth, wrist girth, thigh girth, calf girth, ankle girth, biacromial (shoulder width in layman's terms ) and biiliocristal-breadths (hip width in layman's terms).

Upper arm length was measured from landmarks placed to acromiale and dactylion while athletes stood in the erect position. Upper arm length was determined as the distance between the marked acromiale and radiale landmarks. The lower-arm length was measured by calculating the distance between the radiale and stylion landmarks. For the hand length, the measure was taken as the shortest distance from the marked midstylion line to the dactylion. Lower limb length was determined by subtracting sitting height from standing height. Thigh length was determined as the distance between the marked trochanterion and tibiale lateral landmarks. Leg length was measured as the distance from the height of the tibiale lateral to the top of the box (or the floor). Foot length was determined as the distance from the Akropodion (i.e., the tip of the longest toe which may be the first or second phalanx) to the Pternion (i.e., most posterior point on the calcaneus of the foot). Arm-relaxed girth was measured at the marked level of the mid-acromiale-radiale. The tape was positioned perpendicular to the long axis of the arm.

Forearm girth was taken at the maximum girth of the forearm distal to the humeral epicondyles. Wrist girth measurement is taken distal to the styloid processes. It is the minimum girth in this region. Thigh girth measure was taken at the marked mid-trochanterion-tibiale-lateral site. Calf girth was defined as the maximum girth of the calf taken at the marked medial calf skinfold site. Ankle girth was defined as the minimum girth of the ankle taken at the narrowest point superior to the Sphyrion tibiale. Biacromial breadths were determined as the distance between the most lateral points of the acromion processes. Biiliocristal breath was defined as the distance between the most lateral points on the iliac crests. All somatic measures were recorded twice and the mean scores were retained for the statistical analysis.

**Swimming performance quantification**

The swimming times and/or speeds expressed in seconds and meters per second ($m.s^{-1}$), respectively, were adopted as our measures of swimming performance. Swimming performance was recorded in a 25-m swimming pool. The average speed was calculated as the ratio between distances swam and the total time recorded at this distance ($m.s^{-1}$). The performance times were measured with electronic timing (Omega, Switzerland) and were obtained for all swimmers from official results published by the Tunisian swimming Federation during the Winter National Championships. Water temperature was kept between 25 and 28 degrees, as determined by Fédération Internationale De Natation (FINA, 2014).

Descriptive statistics (means±SD) of all the swimming performance, demographic and somatic measurements by sex and stroke are given in Table 1.

**Table 1 about here**

**Statistical Methods**

To identify the optimal demographic and somatic measurements, including body mass (M), stature (H), percentage body fat (BF%) and limb dimensions (lengths and girths) (LD), associated with 100 m swimming speeds (SS) ($m.s^{-1}$) in all four strokes having controlled for age, we adopted the following multiplicative model with allometric body-size components similar to those used to model the front-crawl swim speeds adopted by Nevill et al. (2015).

$$SS\ (m.s^{-1}) = a \cdot (M)^{k_1} \cdot (H)^{k_2} \cdot (BF\%)^{k_3} \cdot \Pi\ (LD_i)^{k_i} \cdot \exp(\ b\cdot age + c\cdot age^2 + d\cdot MO) \cdot \varepsilon. \qquad (1)$$

where 'a' is a constant and $\Pi\ (LD_i)^{k_i}$ (i=4, 5, …,) represents the product of limb segment-dimensions raised to the power $k_i$; with i=4 being the Sitting height, 5= Upper limb length, 6= Upper arm length, 7= Lower arm length, etc. (see list of variables in Table 1) and MO is the maturity offset (Mirwald et al., 2002). This model has the advantages of having proportional body-size components and the flexibility of a non-linear quadratic in age within an exponential term that will ensure that the 100 m swim speeds will always remain non-negative irrespective of the child or adolescent's age (see Figure 1). Note that the multiplicative error ratio 'ε' assumes the error will increase in proportion to the child's swim-speed performance.

**Figure 1 about here**

The model (Eq. 1) can be linearized with a log transformation. A linear regression on ln(SS) (ln=natural logarithms) can then be used to estimate the unknown parameters of the log-transformed model:

$$Ln(SS)=\ln(a)+k_1\cdot\ln(M)+k_2\cdot\ln(H)+k_3\cdot\ln(BF\%)+\Sigma k_i\cdot\ln(LD_i)+b\cdot age+c\cdot age^2+d\cdot MO+\ln(\varepsilon). \quad (2)$$

Having fitted the saturated model (all available demographic, somatic and body size variables), an appropriate 'parsimonious' model can be obtained using '*backward elimination*' Draper and Smith, 1998) in which at each step the least important (non-significant) body size and limb segment dimensions variable is dropped from the current model. Further categorical or group differences within the population, e.g. sex and swim stroke, can be explored by allowing the constant intercept parameter 'ln(a)' in Eq. 2 to vary for each group (by introducing them as fixed factors and associated interactions within an ANCOVA). The significance level was set at $P<0.05$. Practical importance (meaningfulness) was assessed by reporting effect sizes (partial eta squared = $\eta^2$) as recommended by Winter et al., (2014) Given that some swimmers contributed to more than one cohort (with measurements taken on different occasions), the data can be treated as repeated measurements with a hierarchical structure. For this reason, we repeated the above analysis using multilevel modeling with the statistical software MLwin that allows the different swimmers to be treated as the level 2 hierarchy and their different performance speeds to be at the level 1 hierarchy (see Watts et al., 2012).

**Results**

The parsimonious solution to the backward elimination regression analysis of log-transformed swim speed (Ln(SS)) resulted in the following multiple regressions model (Table 2):

**Table 2 about here**

The multiplicative allometric model relating 100-m swim speeds ($m.s^{-1}$) to the predictor variables found the percentage body fat Ln(BF%) as the only "whole-body" predictor of Ln(SS) (body mass and stature were dropped from the analysis). Six other predictors in addition to the percentage body fat (Ln(BF%)) were found to be significantly associated with Ln(SS), all found to be commonly associated with the four strokes. These were Ln(arm span), Ln(biacromial breadth), Ln(biiliac breadth), Ln(forearm girth), that were positively associated with SS, and Ln(lower arm length) and Ln(relaxed arm girth) that were both negatively associated with SS performance.

Four other predictor variables were also found to be strongly associated with Ln(SS), BUT these associations varied significantly with the 4 different strokes. These were identified by introducing stroke-by-predictor variable interactions (see statistical methods). The 4 significant interactions were "stroke-by-age" ($F_{3,335}$=9.068; $\eta^2$= 0.075, P<0.001), "stroke-by-sitting height" ($F_{3,335}$=4.12; ; $\eta^2$= 0.036, P=0.007), "stroke-by-calf girth" ($F_{3,335}$=6.48; ; $\eta^2$=

0.055, P<0.001), and “stroke-by-ankle girth” ($F_{3,335}$=4.59; ; $\eta^2$= 0.040, P=0.004) (see table 2). Our allometric model also detected a significant sex difference with male swimmers able to swim 3.3% faster than female swimmers (Table 2). The adjusted coefficient of determination, adjusted $R^2$ for the fitted multiplicative allometric model was 88.3% with the log-transformed error ratio being 0.068 or 7.08%, having taken antilogs.

As stated in the methods, given that some of the swimmers contributed to more than one cohort, the hierarchical or repeated-measures nature of these data was re-analyzed using the multilevel modelling statistical software MLwin. The results are given in Table 3.

**Table 3 about here**

**Discussion**

There is compelling evidence that anthropometric and somatic characteristics play a key role in the early identification of talented/gifted athletes (Issurin, 2017). This is because such characteristics are more genetically determined and less trainable than most physical fitness attributes (Issurin, 2017). For instance, it has been established that anthropometrics such as body length (e.g., height, limb lengths and feet) are strongly determined by genetics (level of inherence of 70%) (Bouchard, Malina, & Perusse, 1997; Szopa, Mleczko, E., & Zychowska, 1999). The present study used an allometric modelling approach and ANCOVA to identify the optimal anthropometric, somatic and demographic characteristics (as covariates) associated with 100-m swimming performances (average speeds in $m.s^{-1}$) in four swimming-stroke cohorts (back stroke, breast stroke, butterfly and front crawl) based in Tunisia. We recognise that some swimmers contributed to more than one cohort, so when we re-analysed the data using multilevel modelling that takes these repeated measurements into account, the results were remarkably similar (see table 3 vs. table 2) and our conclusions remained the same. For the sake of simplicity, we shall focus our discussion on the first of the two analyses (Table 2).

The results identified seven predictor variables that were common to all strokes (see Table 1) together with another 4 characteristics that would appear to benefit some strokes significantly more than others (identified by stroke-by-predictor variable interactions). The total explained variance of these predictor variables was 88.3% (adjusted $R^2$) although we acknowledge that the majority of the effect sizes were relatively modest, between small and moderate (http://imaging.mrc-cbu.cam.ac.uk/statswiki/FAQ/effectSize)

Of the seven "common" predictor variables, percentage body fat (Ln(BF%)) was the single most important "whole-body" size characteristic (B=-0.089, SE=0.018; P<0.001). Unsurprisingly, having a lower BF% benefits all 4 strokes. Stature and body mass did not contribute significantly to the parsimonious allometric model, suggesting that the advantage of having longer levers and/or greater girth dimensions was "limb specific" rather than a more general whole-body advantage.

The four positive "common" predictor variables associated with swim speed were Ln(arm span), Ln(biiliac breadth) or hip width in layman's terms, Ln(biacromial breadth) or shoulder width in layman's terms, and Ln(forearm girth). The two negative "common" characteristics associated with swim speed were Ln(lower-arm length) and Ln(arm-relaxed girth). Taken together, swimmers from all four strokes appear to benefit from broad shoulders and hips, a greater arm span (but with relatively short lower arms) and greater forearm girths but smaller relaxed arm girths.

Having taken anti-logs, the two common "arm length" predictors can be combined for form an "arm span"-by-"lower arm" ratio given by the ratio=(arm span)^0.327/(lower arm length)^0.247 (see Table 2 for exponents) that highlights the advantage of having a greater arm span but also highlights a possible disadvantage of having a too greater lower-arm length. Similarly, the two common arm girth predictors can be combined to form a common "arm-girth" ratio given by the ratio=(forearm girth)^0.409/(relaxed arm girth)^0.272 (see Table 2 for the exponents). This ratio was also identified by Sammoud et al. (2019) as key to backstroke swimming performance. The authors suggested that the “arm girth” ratio was possibly reflecting a measure of muscularity, i.e., with the muscularity component resulting from the flexed vs. non-flexed girth ratio.

However, from a talent identification point of view, the 4 stroke-by-predictor variable interactions provide the most illuminating new insights. The significant stroke-by-sitting height interaction reveals that backstroke swimmers have the longest sitting heights, a finding that is in direct contrast to the breaststroke swimmers who have the shortest sitting heights. Sammoud et al. (2019a) had already reported a similar finding when identifying key somatic variables associated with young backstroke swimmers, likening the sitting height of a swimmer with the length of a boat’s hull. It is well known that boats with longer hulls travel faster through the water (Charles, 2010). The analogy implied here to backstroke swimming performance is that the longer sitting-height component of the skeleton will also reflect the benefits of a longer boat’s hull when traveling through the water (although this analogy is not unanimously accepted since backstroke, being a rotational stroke along the longitudinal axis, and breaststroke, being a rotational stroke along the transverse axis, have fundamentally different dynamics).

The stroke-by-calf girth interaction together with the stroke-by-ankle girth interaction can also be considered operating together. Inspection of the two interactions in Table 2 reveals that the stroke associated with greatest calf girth is also the stroke with the smallest ankle girth, namely the butterfly. Again having taken antilogs, butterfly swimmers are characterized by having the greatest “calf girth”-to-“ankle girth” ratio, given by (calf girth)^0.515/(ankle girth)^0.522. We can speculate that this ratio is likely to reflect the greater muscularity in the lower leg associated with butterfly swimmers. However, the ratio is specific to butterfly swimmers alone and cannot be considered as an important indicator of swimmers from the other three strokes.

The regression analysis also identified a significant stroke–by-age interaction (see Table 2). In our original model specification, see the statistical methods section (Eq.1), we anticipated a curvilinear association between swim speed and age, justified by the apparent curvature observed in Figure 1 and the necessity to include the quadratic age terms in Eq. 1. In reality, much of the apparent curvature can be explained by the different age slopes observed for the different strokes, with the steepest slope observed in breaststroke swimmers and the shallowest slope identified with the front crawl swimmers, see Figure 1.

## Conclusion

In summary, the present study revealed 7 “common” characteristics that benefit all swimmers, and 4 other characteristics that benefit some but not all swimmers. Taken together, the 7 “common” characteristics suggest that all swimmers benefit from having less body fat, broad shoulders and hips, a greater arm span (but shorter lower arms) and greater forearm girths with smaller relaxed arm girths. The 4 stroke-specific characteristics reveal that backstroke swimmers benefit from longer backs, a finding that can be likened to boats with longer hulls also travel faster through the water. The stroke-by-calf girth and the stroke-by-ankle girth interactions taken together identified butterfly swimmers with having the greater calf girths but also the smaller ankle girths, i.e., faster butterfly swimmers are characterized by greater muscularity in the lower legs. These results highlight the importance of considering key somatic characteristics of young swimmers for talent identification purposes (i.e., to ensure that swimmers realize their most appropriate strokes).

## Disclosure statement

No potential conflict of interest was reported by the authors.

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## FIGURE CAPTIONS

**Figure 1.** The relationship between 100-m swim speeds and age by stroke.

## TABLE CAPTIONS

**Table 1** The mean and standard deviation (±SD) of swimming performance, demographic and somatic measurements by sex and the 4 strokes.

**Table 2** The parsimonious solution to the backward elimination regression analysis to predict log-transformed swim speeds (Ln(SS)) given by Eq. 2

**Table 3** The parsimonious solution to the backward elimination regression analysis to predict log-transformed swim speeds (Ln(SS)) using multilevel modelling (MLwin).